# Gear Surface Durability Development to Enhance Transmission Power Density

**Joe Chen, John Flynn and Geoff Semrau**

### Introduction

Gear pitting is one of the primary failure modes of automotive transmission gear sets. Over the past years, many alternatives have been intended to improve their gear surface durability. However, due to the nature of new process development, it takes a length of time and joint efforts between the development team and suppliers to investigate and verify each new approach.

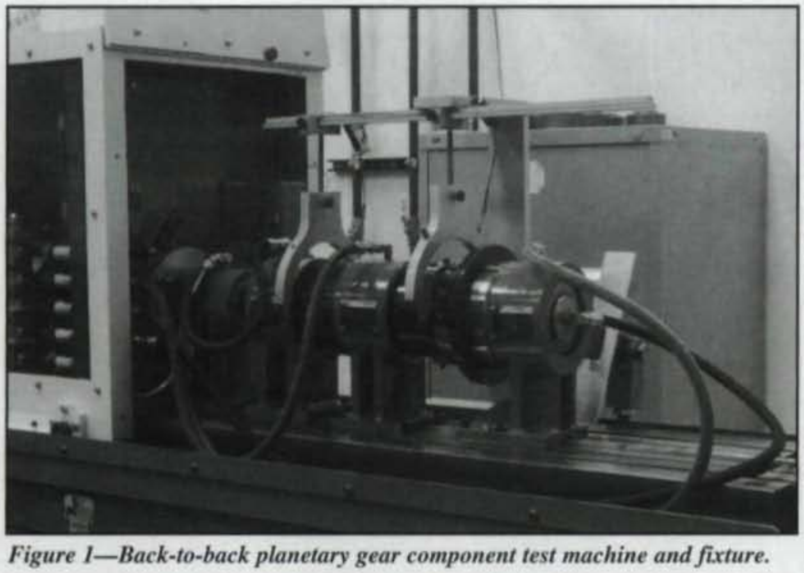


*Figure 1—Back-to-back planetary gear component test machine and fixture.*

**Table 1—Test Matrix for Surface Durability Comparison**

| | | | | | | |
|---|---|---|---|---|---|---|
| **1. Baseline vs. Redesign** | | | | | | |
| **2. Material Selection—Sun Gear Only, Use Standard Planets & Ring Gear for Testing** | | | | | | |
| **Sun Gear Materials** | | | | | | |
| AISI/SAE (U.S.A.) Steels | | | | European Steels | | |
| 4620M Baseline | 8620 | 9310 | 5120 | 18CD4 | 25CD4 | 30CD4 |
| X | X | X | X | X | X | X |
| **3. Manufacturing Process—Use Standard Ring Gear for Testing** | | | | | | |
| **Sun Gear Process** | | | | | | |
| Planets | Baseline | Honed | Coating | Dual Shot Peening | Isotropic 1 | Isotropic 2 |
| Prod. planet | X | X | X | X | | |
| Without Shot Deburring | X | | | | | |
| Honed Planets | X | X | | | | |
| Isotropic 1 | | | | | X | |
| Isotropic 2 | | | | | | X |

New and upgraded transmissions have required a higher input power capability to meet the customers' expectations. Increasing the power density in the transmission gear system was urgently demanded. To shorten the development time in this area, GM Powertrain's Advanced Gear Systems Group initiated a systematic approach to evaluate alternatives that had the potential to meet the needs. In addition to a single-tooth bending project for a gear bending fatigue study and joint projects with bearing suppliers to improve the durability of planetary bearings (Ref. 1), a comprehensive gear surface durability improvement project was established.

This study is a preliminary assessment of the effects of applying different design methodologies, material selections and manufacturing processes on gear surface durability. Based on this analysis, an in-depth study will follow to further understand the benefits of using different alternatives for future applications.

### Objectives of the Study

- To evaluate and verify the effects of design, material selection and manufacturing process on power density of planetary transmission gear sets.
- To examine and interpret the effects of factors, such as surface roughness, residual stress, coating, material properties and geometry variations on gear surface durability.
- To understand benefit and risk factors of each variant for future applications.

### Methodology

All tests were conducted at the GM Powertrain Gear Laboratory using a back-to-back planetary gear component test machine with a specially designed test fixture (Fig.1). An existing planetary gear set was chosen as the baseline because its surface durability characteristics were well known, and its design permitted easy inspection and maintenance.

The test matrix for the surface durability study is shown in Table 1. It consists of two different design approaches, seven material selections, and nine manufacturing processes.

Design specifications and stress calculations are shown in Table 2. The stresses are based on a torque of 1,500 N-m at the ring gear. Lead taper is not considered in the stress calculations.

The test samples were thoroughly inspected before the test. Relevant features of each test part were identified and recorded for future reference.

The gears were originally tested at a constant torque of 1,500 N-m at the reaction arm and a constant speed of 1,500 rpm at the input spindle. Under these conditions, however, the redesigned gear set did not pit in a reasonable period of time and displayed inconsistent failure modes. Increasing the torque to 2,000 N-m produced the desired results.

The test matrix was run in a random pattern to satisfy the statistical requirement for a small sample size. The random pattern is also helpful in detecting faults in the machine and fixture settings during testing.

Failure was achieved when any tooth flank developed a pit with an area of 1.0 $mm^2$ at a depth exceeding 1.5 mm. Pit size was measured by a computerized optical image device, and pit depth was assessed with a gear profile inspection machine.

A Weibull analysis (Ref. 2) was performed to establish life ranks.

A metallurgical failure analysis was performed on selected samples for a better understanding of the causes of the failure.

### Test Results

***Design Approach.*** The baseline planetary gear set was designed approximately 20 years ago and has been used in various transmissions since then. Recently, increased engine power and more stringent noise specifications caused this design to become obsolete. A new gear set, with enhanced capabilities but fitting in the same space, was then produced. The design approaches of these two gear systems are quite different. The original design used a relatively coarse pitch to enhance the tooth bending strength and adopted lead taper to reduce the gear force fluctuation.

The use of taper moderates vibration levels by preventing the sudden release of load at the tooth trailing end (Ref. 3). The redesign uses a finer pitch to increase both involute and helical contact ratios and incorporates profile modifications to optimize the load distribution. Based on 3-D FEA modeling, the new design has better load distribution and lower overall tooth compressive stress than the baseline gear set. Noise and vibration tests verified that the new design has a substantially lower gear mesh noise level (Fig. 2).

As was mentioned above, the two designs were tested under different loading conditions. Figure 3 shows the pitting life comparison between the baseline and redesigned gear sets. Figure 4 shows the corresponding Weibull analy-

**Table 2—Design Comparison**

| | Design | |
|---|---|---|
| | **Base Design** | **Redesign** |
| Normal Module | 1.630 | 1.439 |
| Gear Ratio | 3.33 | 3.29 |
| Normal Pressure Angle | 20.00 | 19.00 |
| Helix Angle | 18.00 | 20.00 |
| Total Contact Ratio | 2.69 | 3.63 |
| Lead Modification | 0–36 μm | 0 +/– 18 μm |
| | **Stress Comparison** | |
| | **Base Design** | **Redesign** |
| Bending (MPa) | 512 | 513 |
| Compressive (MPa) | 1,510 | 1,250 |

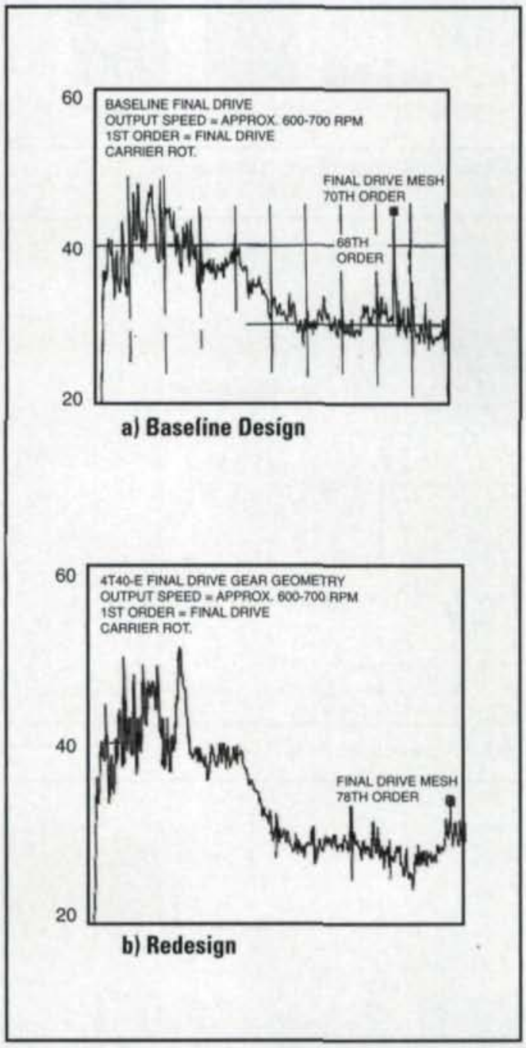



*Figure 2—Gear noise and vibration level comparison.*


**Joe Chen**

*is a staff project engineer with GM Powertrain Gear Center in Wixom, MI. He holds a master of science degree in mechanical engineering, as well as a master's degree in business administration. He has more than 25 years of experience in gear system design and development for on- and off-highway transmissions.*

**John Flynn**

*is a senior project engineer with the GM Powertrain Gear Center and the GM Powertrain Application Group. He holds a bachelor's degree in metallurgical engineering and a master's degree in business administration. He has more than 11 years of experience in metallurgical and failure analysis.*

**Geoff Semrau**

*is a senior project engineer with the GM Powertrain Base Transmission Group. He holds a master of science degree in mechanical engineering. He has been with GM Powertrain for 18 years, and he specializes in gear system development and analysis.*

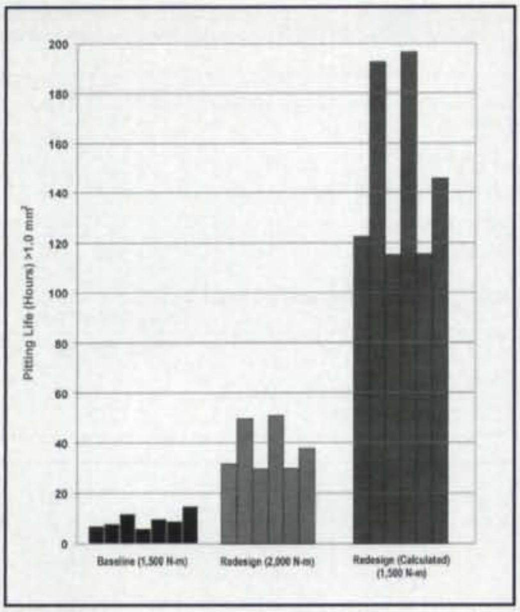



*Figure 3—Sun gear pitting life comparison between designs.*

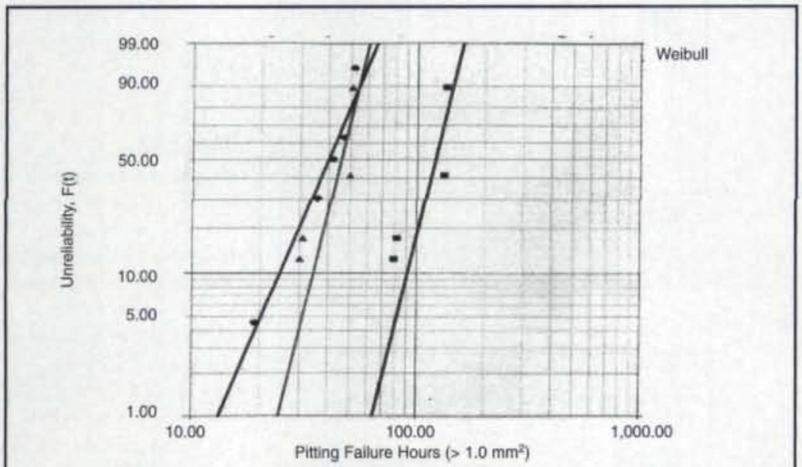



*Figure 4—Weibull analysis for design comparison.*

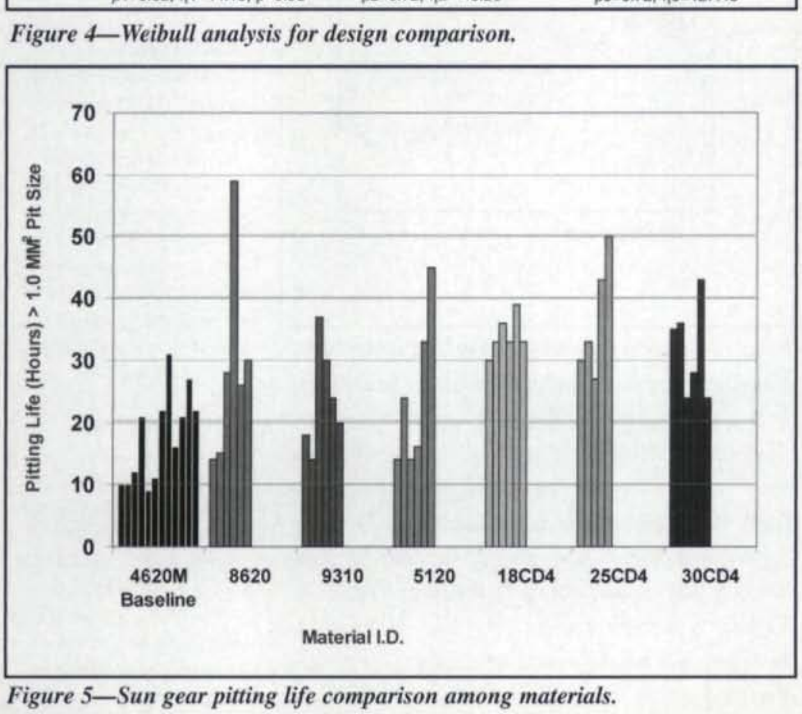



*Figure 5—Sun gear pitting life comparison among materials.*

sis result of these two design approaches. The analysis shows that the baseline coarser pitch sun gear has a B-50 pitting life of 40 hours. This compares to 46 hours at the higher load or 120 hours at the same load for the finer pitch gear set. The 120 hours is determined by extrapolation using an S/N curve with slope of 3.375. The data indicate that a significant improvement in pitting life has been achieved by the redesign.

***Material Selection.*** Seven common gear steels were selected for surface durability testing. Figure 5 shows the surface durability test results, and Figure 6 shows the Weibull analysis. The sample gears were identical in design and manufacture. Several parameters possibly affecting surface durability were tabulated. Table 3 shows the chemical composition, retained austenite, case depth and hardness of each material. Table 4 shows a comparison of surface finishes.

***Manufacturing Processes.*** Seven different manufacturing processes were evaluated. Both sun and pinion gears were fabricated using the various processes, and a total of nine combinations were tested (Table 1). Standard ring gears were used for all tests. To eliminate unwanted variations, the test gears—except those to be honed—were manufactured and heat treated as a single lot and later finished by the specific method. Figure 7 shows the durability life comparison of the manufacturing processes, and Figure 8 shows the Weibull analysis that ranks all the test variants.

The test results reveal that manufacturing processes can have a significant effect on the surface durability. While further investigation is needed, some general observations may be made:

The surface finish of the planet pinions has a great influence on the sun gear durability. This is illustrated as follows:

- Honed sun gears run with standard pinions have only one-third the life of standard sun gears run with honed pinions. The honed pinions have a better surface finish than the standard pinions.
- Honed sun gears run with standard pinions have approximately one-fourth the life of honed sun gears run with honed pinions.
- The shot deburring process, which is intended to remove gear edge burrs and heat-treatment scale, is detrimental to gear life if poorly controlled. Standard sun gears run with pinions that were not subjected to shot deburring have four times the life of the standard sun gears run with pinions that were shot deburred. The shot deburring process produces much rougher sur-

faces on the gear teeth and, if not under tight control, can cause severe surface damage. Figure 10 shows a comparison of gear teeth before and after a poorly controlled shot deburring operation.

Both isotropic surface finishing processes (Ref. 4) use a sequence of chemical and mechanical operations to smooth the gear surface by removing a few micrometers of material. One of these proprietary processes appears to have the potential of enhancing surface durability when both mating gears are treated.

Compressive residual stress near the tooth fillet has long been recognized as contributing to increased gear tooth bending life. The same theory can also be applied to gear surface durability (Ref. 5) with a certain degree of success. It is imperative, however, that the gear surface is not substantially damaged by the process used to impart that compressive residual stress. Figure 10 shows the comparison of the residual stress produced by the conventional and two secondary processes. The dual shot peening and the honing process, both completed after heat treatment, add compressive residual stress to the gear surface. These stresses will reduce surface crack progression and thus increase useful gear life. The dual shot peening requires two different shot sizes and intensities. The coarser shot provides deep penetration at the root, and the finer shot produces high compressive residual stress close to the surface. Similarly, the honing process provides high compressive residual stress close to the tooth surface.

All test variants except the honed parts were conventionally hobbed and shaved and then batch heat-treated. However, tooth profile distortion during heat treatment is not consistent from lot to lot or even part to part. Because the honing process is completed after heat-treating, better profile consistency can be achieved.

Table 5 shows a comparison of the profile control obtained by the conventional and honing processes. The much improved surface durability of the honed sun and planet result from the combination of benefits from consistent geometrical control and higher residual compressive stress.

Gear surface hardness is essential to sustain extended gear life. Non-metallic coatings can provide very high surface hardness (HRc 90) and lower friction coefficients. The non-coated samples in this study had conventional surface and core hardness. The mechanism by which

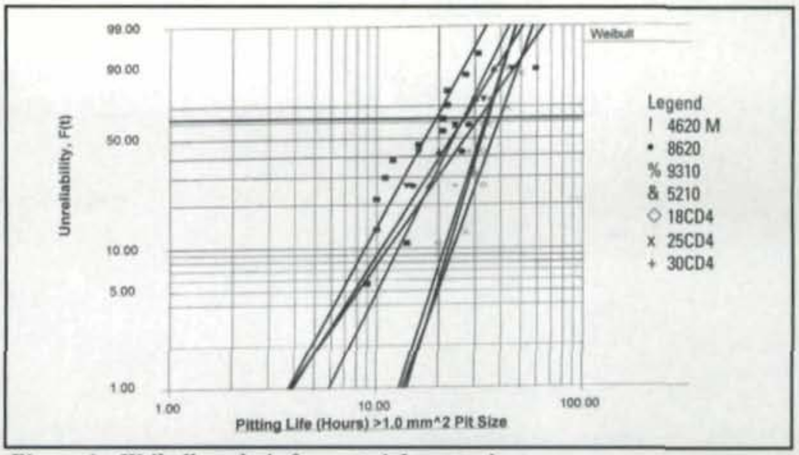



*Figure 6—Weibull analysis for material comparison.*

**Table 3—Material Chemical Compositions and Metallurgical Analyses**

| Material | C | Si | Mn | P | S | Ni | Cr | Mo |
|---|---|---|---|---|---|---|---|---|
| AISI 4620 | 0.17/0.23 | 0.15/0.35 | 0.35/0.75 | 0.35 Max | 0.35 Max | 1.55/2.00 | 0.20 Max | 0.20/0.30 |
| AISI 4620M | 0.17/0.23 | 0.15/0.35 | 0.35/0.75 | 0.35 Max | 0.35 Max | 1.55/2.00 | 0.20 Max | 0.50/0.70 |
| AISI 8620 | 0.17/0.24 | 0.15/0.35 | 0.60/0.95 | 0.35 Max | 0.35 Max | 0.35/0.75 | 0.35/0.65 | 0.15/0.25 |
| AISI 5120 | 0.17/0.22 | 0.15/0.36 | 0.70/0.90 | 0.35 Max | 0.40 Max | 0.20 Max | 0.70/0.90 | 0.03 Max |
| AISI 9310 | 0.07/0.13 | 0.15/0.30 | 0.40/0.70 | 0.35 Max | 0.40 Max | 2.95/3.55 | 1.00/1.45 | 0.08/0.15 |
| AFNOR 18CD4* | 0.15/0.22 | 0.10/0.40 | 0.60/0.90 | 0.35 Max | 0.35 Max | 0.20 Max | 0.85/1.15 | 0.15/0.35 |
| AFNOR 25CD4* | 0.22/0.28 | 0.10/0.40 | 0.60/0.90 | 0.35 Max | 0.35 Max | 0.20 Max | 0.90/1.20 | 0.15/0.25 |
| AFNOR 30CD4* | 0.27/0.33 | 0.10/0.40 | 0.60/0.90 | 0.35 Max | 0.35 Max | 0.20 Max | 0.90/1.21 | 0.16/0.26 |

* European Material – similar to AISI 41XX family

| Inspection | Spec. | 4620M | 9310 | 18CD4 | 5210 | 8620 |
|---|---|---|---|---|---|---|
| Retained Austenite (%) | | 9 | 8 | 21 | 23 | 3 |
| Surface Residual Stress (MPa) | | –820 | –634 | –220 | –110 | –613 |
| Total Case Depth (1/2 Height) | 0.40–0.56 | 0.45 | 0.45 | 0.55 | 0.45 | 0.45 |
| Total Case Depth (Root) | | 0.40 | 0.40 | 0.50 | 0.50 | 0.40 |
| Effective Case Depth @ 1/2 Height | | 0.35 | 0.25 | 0.25 | 0.25 | 0.35 |
| Effective Case Depth @ Root | | 0.40 | 0.25 | 0.25 | 0.25 | 0.35 |
| Core Hardness (HRc) | 32/44 | 43 | 38 | 36 | 33 | 41 |
| Surface Hardness (HR30N) A-scale | 75.5/79.0 | 77 | 76 | 76 | 76 | 76 |

**Table 4—Surface Finish Comparison**

| Finish Term | 4620M test side | 5120 test side | 18CD4 test side | 25CD4 test side | 30CD4 test side |
|---|---|---|---|---|---|
| Ra (μm) | 0.238 | 0.245 | 0.202 | 0.254 | 0.213 |
| Rsk | 0.032 | –2.187 | –0.814 | –2.334 | –0.357 |
| PV (μm) | 8.198 | 8.179 | 2.315 | 5.947 | 3.345 |
| Rms (μm) | 0.310 | 0.350 | 0.270 | 0.190 | 0.740 |

Ra (μm) The average surface roughness
Rsk Skewness, a measure of symmetry of valleys; a positive skew indicates a "peaky" surface
PV (μm) Maximum peak-to-valley height over the sample
Rms (μm) The root-mean-square average of the measured height deviation taken within the evaluation area and measured from the mean surface

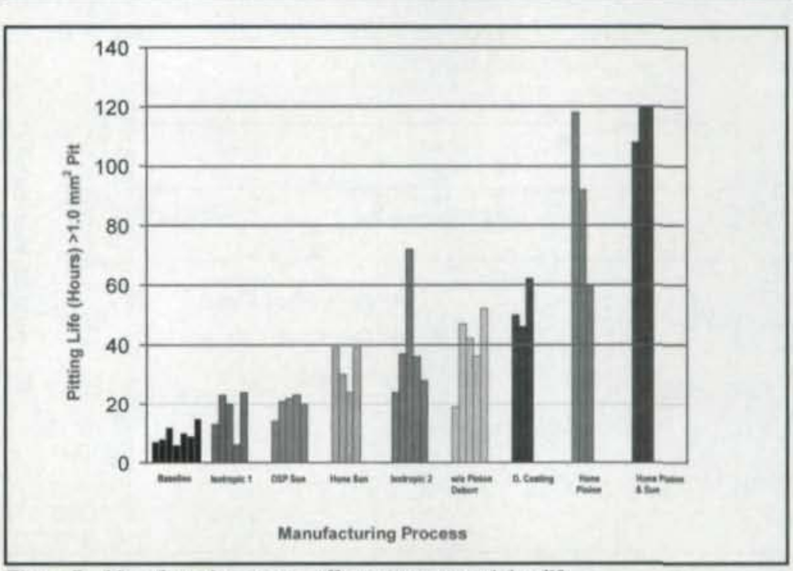



*Figure 7—Manufacturing process effect on sun gear pitting life.*

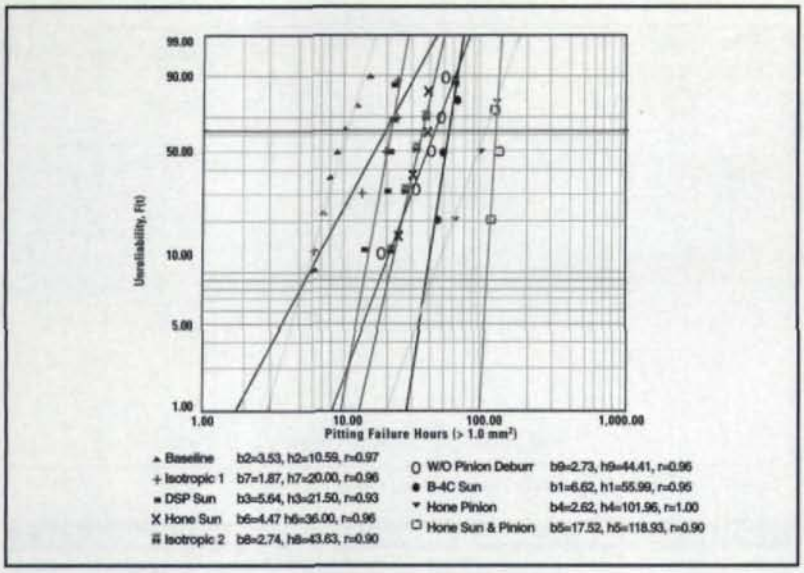



*Figure 8—Weibull analysis for process comparison.*

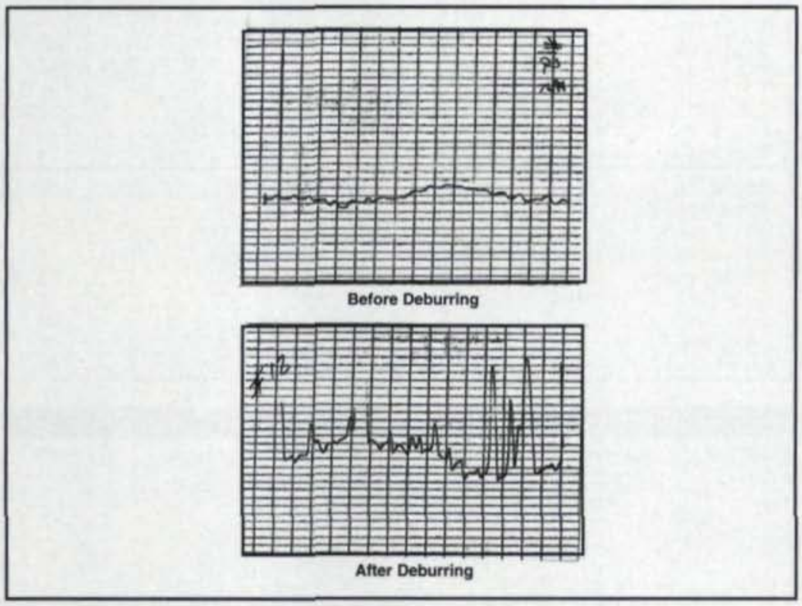



*Figure 9—Planet surface roughness before and after shot deburring process.*

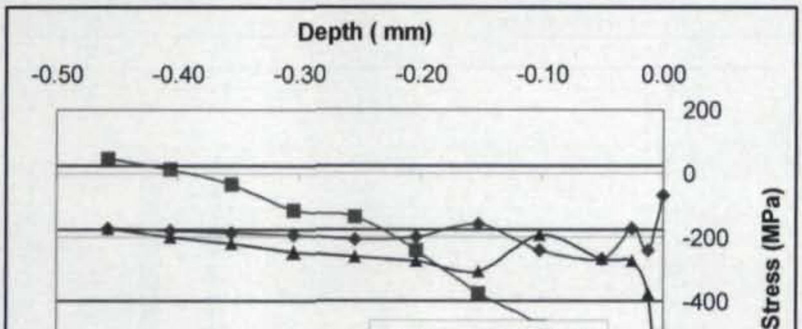



*Figure 10—Residual stresses produced by different manufacturing processes.*

coatings provide improved surface durability is not fully understood at this time and is the subject of continuing research.

Figure 11 shows typical microstructure photographs of tested samples. Failure analysis conducted by the GM Pow-ertrain Gear Laboratory revealed that most distress is surface-initiated fine grain pitting. Surface cracks initiating at inclusions were also found. The inclusions may have been non-metallic impurities in the steel or could have been caused by a manufacturing operation. There were also findings of intergranular oxidation (IGO), related to the high alloy content of the steel and improper environment control during heat treatment.

## Conclusions

Two similar planetary gear sets with different design approaches were tested to compare surface endurance life. The redesigned finer pitch gear set has about three times the B-50 life of the baseline coarser pitch gear set.

Stress calculations show that the finer pitch gear set has about 21% lower compressive stresses and better load sharing than the baseline coarser pitch design. The redesigned gear set utilizes finer pitch to increase the involute and helical contact ratios and employs tooth profile modifications to prevent uneven load distribution along the line of tooth action.

Seven different gear steels were tested. All samples were manufactured and heat-treated by identical processes. Weibull B-50 lives for sun gears between the baseline and the best performing steel were spread from 18 hours to 37 hours respectively. The life ranks from the lowest to the highest are: 4620M (baseline), SAE-9310, SAE-5120, SAE-8620, 30CD4, 18CD4 and 25CD4. The last three steels are European products.

Although the chemical composition, surface finish, and microstructure of these materials were closely examined, no conclusive explanation of their varying surface durability can be made.

Nine different manufacturing processes were tested. Except for the honed gears, all test parts were identically manufactured and heat-treated. Secondary processes were then completed to enhance the power density capability. Weibull B-50 lives between the baseline and the best performing samples were spread from 9.5 hours to 115 hours. The gear surface lives among the test variants are ranked from lowest to highest as follows: baseline (standard) process (1), isotropic 1 (2), double shot-peened sun gear (3), honed sun gear with standard pinions (4), isotropic 2 (5), standard sun gears mated with pinions that were not shot deburred (6), non-metallic coated sun gear (7), standard sun gears with honed pinions (8), and sun gears and pinions both honed (9). Among the characteristics producing significant surface durability improvement are the surface finish, the residual stress pattern, the surface hardness, and superior tooth geometry control.

Planet tooth surface roughness appears to have a significant effect on the sun gear surface durability. ○


### Acknowledgments

The accomplishment of this project occurred through the joint efforts of all the project team members, the manufacturing facility of GMPT-St. Catharine and GM Powertrain gear test and inspection laboratories. The authors would also like to express their appreciation to those who provided assistance and information to this project.


### References


1. Chen, J. "Planetary Needle Bearing Development to Enhance Transmission Power Density," To be published.
2. *PC-WAS Weibull Analysis System User Guide,* developed by EDS Group, March 1993.
3. Hardy, A. "An Action Analysis of Gear Teeth With Modified Lead and Profile," SAE 670050.
4. Hashimoto, F. "Modeling and Optimization of Vibratory Finishing Process," *Annals of CIPP*, Vol. 45, January 1996.
5. Simpson, R. and R. Garibay. "Quantification of Shot Peening Process Variables Affecting Workpiece Performance—Process Control and Double Shot Peening Media," SAE-850714.

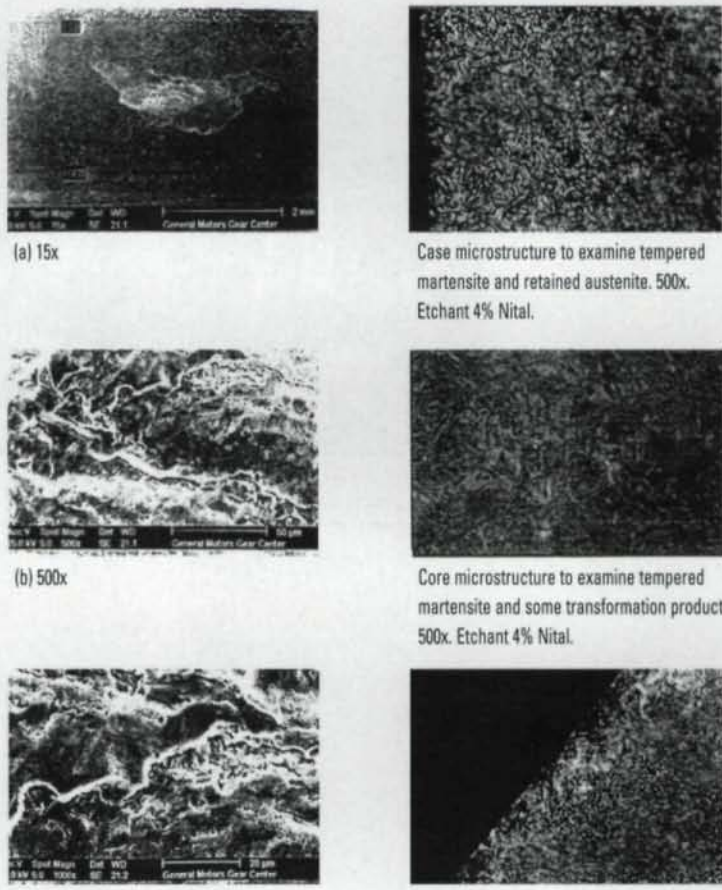


**This article was first published in the Proceedings of the International Conference on Mechanical Transmissions, held in April 2001 in Chongqing, China.**




**Table 5—Comparison of Geometry Control between Conventionally Manufactured Gears and Honed Gears**

| Units in Metric | | | [1] | | [2] | |
|---|---|---|---|---|---|---|
| | Spec. Tolerance | Production | | Honed By Nachi Machine | | [2]/[1] |
| Sun Gear | for CP | 6 Std. Deviation | CP | 6 Std. Deviation | CP | % |
| Diameter over Balls | 0.132 | 0.062 | 2.13 | 0.03 | 4.4 | 207% |
| Lead Average | 0.036 | 0.026 | 1.38 | 0.006 | 6 | 433% |
| Lead Crown | 0.01 | 0.009 | 1.11 | 0.004 | 2.63 | 237% |
| Lead Variation | 0.038 | 0.036 | 1.06 | 0.019 | 2 | 189% |
| Involute Average | 0.026 | 0.013 | 2 | 0.005 | 5.2 | 260% |
| Involute Crown | 0.01 | 0.006 | 1.67 | 0.003 | 4 | 240% |
| Involute Variation | 0.038 | .018 | 2.11 | 0.012 | 3.17 | 150% |
| Total Pitch Runout | 0.1 | 0.062 | 1.61 | 0.034 | 2.94 | 182% |
| | Spec. Tolerance | Production | | Honed By Nachi Machine | | [2]/[1] |
| Planet | for CP | 6 Std. Deviation | CP | 6 Std. Deviation | CP | % |
| Diameter over Balls | 0.095 | 0.05 | 1.9 | 0.02 | 4.75 | 250% |
| Lead Average | 0.036 | 0.037 | 0.97 | 0.004 | 10.29 | 1,057% |
| Lead Crown | 0.01 | 0.013 | 0.77 | 0.002 | 6.67 | 867% |
| Lead Variation | 0.038 | 0.05 | 0.76 | 0.015 | 2.53 | 333% |
| Involute Average | 0.026 | 0.025 | 1.04 | 0.003 | 8.67 | 833% |
| Involute Crown | 0.011 | 0.009 | 1.22 | 0.002 | 7.33 | 600% |
| Involute Variation | 0.038 | 0.032 | 1.19 | 0.012 | 3.17 | 267% |
| Total Pitch Runout | 0.038 | 0.042 | 0.9 | 0.019 | 2 | 221% |



(a) 15x

Case microstructure to examine tempered martensite and retained austenite. 500x. Etchant 4% Nital.

(b) 500x

Core microstructure to examine tempered martensite and some transformation products. 500x. Etchant 4% Nital.

(c) 1,000x

Intergrannlar oxidation and inclusion examination near hardened case area. 500x. Etchant 2% Nital.

SEM photographs showing the pit examined.

*Figure 11—Typical microstructure photograph of tested parts.*